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IMPROVING RELIABILITY BY REDUCING TOLERANCE STACK-UP FAILURES

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14. ABSTRACT

Excalibur is the Army's 155-mm guided bullet for howitzers. Once fielded, Excalibur is expected to have a reliability of 90%. This paper describes a method to predict the reliability of the locking mechanism in the fuze safe and arm device. Hand calculations showed that a locking failure could occur if several dimensions were machined close to a tolerance limit in the same device. The probability of a locking failure was estimated using Monte Carlo simulations and a First Order Probability method. The governing equation was a function of about a dozen other equations and 21 variables. A probability distribution function described each variable's nominal dimension and tolerance. Both Monte Carlo simulations and First Order Probability methods predicted fewer than 35 failures in a million devices. Output also included a ranking of dimensions and tolerances and their relative effect on reliability.

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INTRODUCTION

The Army's Excalibur is a 155-mm guided projectile. Excalibur has four key performance parameters: accuracy, effectiveness, reliability, and interoperability. Reliability is the probability that the projectile meets its mission without any failure. One of the precursor projectiles to Excalibur, the 155-mm M898 Sense and Destroy Armor (SADARM), did not meet its key performance parameter for reliability in part due to tolerance stack-up failures in one of its sensors. In several early tests, over-closure caused binding of the sensor and SADARM failed to operate as designed.

A large part of a projectile's mission is to guarantee the safety of the soldiers using the round. For this analysis, reliability deals with the probability that the round is safe when unarmed. Another part of the projectiles mission is that the round arms at the right time. In some cases, the parameters that change the safety of the round also inversely affect the ability for the round to arm itself. A careful balance must be acquired between these two objectives.

To meet Excalibur's reliability parameter of 90%, tolerance stack-up analysis is routinely done on all sensors, mechanisms, and sub-systems. One of the sub-systems effecting reliability is the fuze safe and arm device (FS&A). The FS&A is the mechanism that governs the timely arming of Excalibur.

Figure 1 shows a small part of the FS&A device (more details cannot be shown). For safe operation, the rotor D-lock link must be in the correct position when Excalibur is unarmed. About 20 dimensions affect the accurate positioning of the rotor D-lock within the rotor slot. Each dimension has a tolerance range. Preliminary analysis showed that if several parts were machined to the extreme dimensions of their tolerances, the rotor D-lock would not clear the locking slot and the mechanism would remain (incorrectly) in the unlocked position. This failure would not only lower the reliability of Excalibur, it could render the projectile unsafe.

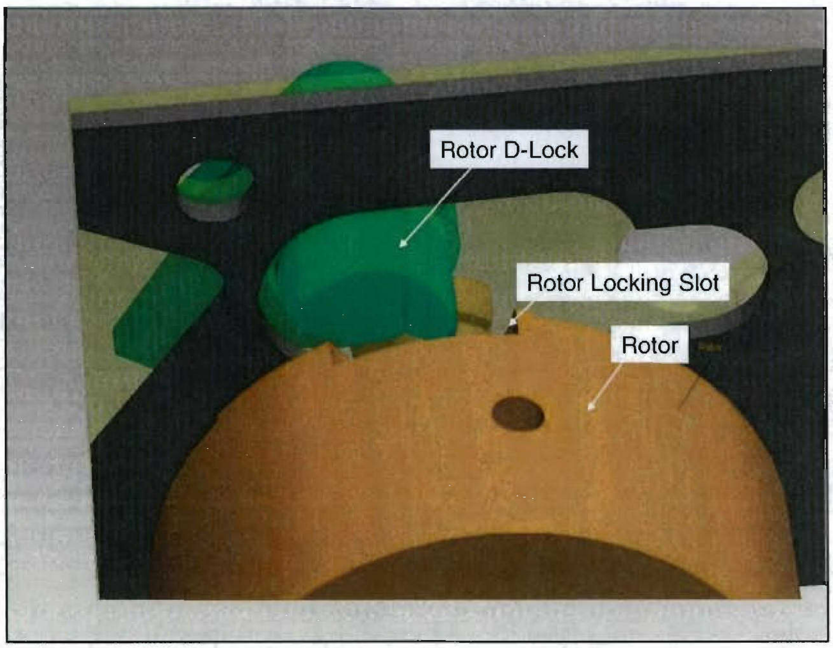


Figure 1
Fuze safe and arm device (small section)

Probabilistic analysis was performed to determine the likelihood that the FS&A would not lock as designed. UNIPASS software (ref. 1) was used to perform the probabilistic analysis. Two probabilistic methods were used to perform the analysis including the Monte Carlo Method and First Order Reliability Method. The Monte Carlo method predicted improper locking would occur less than one time in a million mechanisms. The First Order Reliability method estimated 32 failures in a million mechanisms. The sensitivity measures provided by the First Order Reliability method were used to identify which dimensions and tolerances could be changed to improve reliability.

METHOD

Probability Analysis

The probability of success or failure was defined by mathematical relations between two dimensions in the FS&A device:

$$0 < S1(y) - s2(y) \text{ safe} \quad (1)$$

$$0 \geq S1(y) - s2(y) \text{ fail} \quad (2)$$

where

S1(y) = distance from the datum to top of locking slot

S2(y) = distance from the datum to the bottom most corner of the D-lock

When equation 1 is satisfied, the FS&A operates as designed and the rotor D-lock is locked into the rotor slot.

Two probability simulations were completed to estimate the reliability of the FS&A. First, the Monte Carlo simulation used a high number of iterations. At every iteration, a random value was chosen between the upper and lower limits of each dimension function. A second simulation, a First Order Reliability method (refs. 2 through 4), was used to validate the Monte Carlo simulation. The First Order Reliability simulation used multiple iterations to define a most probable point of failure (MPP). It then varied each dimension from the MPP to determine the probability of failure.

All dimensions were inserted into the analysis as a probability distribution shown in figure 2. Each dimension has a lower limit XL and an upper limit XU. The upper and lower limits were determined from the nominal dimension and its tolerances. For example:

If Dimension = nominal ± tolerance = 100 ± 0.05

Then XL = 99.95 and XU = 100.5

Results were calculated for the 'Hard Boundary' in figure 2. The 'Soft Boundary' might be used for less than 100 % inspection of a dimension or where errors in the inspection occurred. Other possibility distributions could also be used for dimensions.

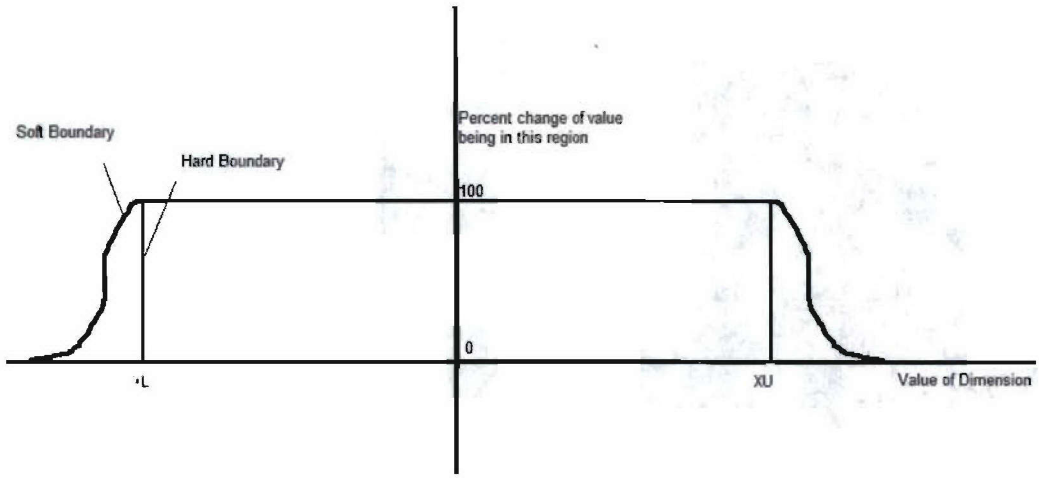


Figure 2
Probability distribution of dimensions

Geometry and Governing Equations for Locking Mechanism

The equations for the dimensions affecting the rotor locking mechanism were generated. Figure 3 shows equations that were used for the probability analysis. Each dimension is referenced from the datum line in figure 3c.

$$0 = s2(y) - S1(y)$$

$$s2(y) = By + (Bh - Rdl)\cdot\sin(bang) + Rdl\cdot\sin(\beta)$$

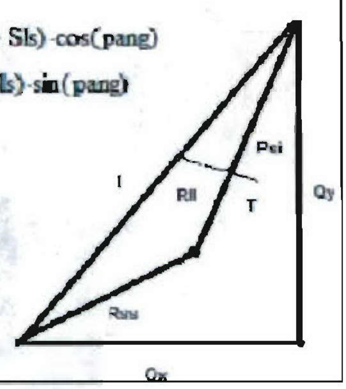
$$S1(y) = Ay + (Ah - axle)\sin(angle) - Rrotor\cdot\sin(\alpha)$$

$$H2 = Qx + (Bh - Rdl)\cdot\cos(bang) + (BSh2 - Sls)\cdot\cos(pang)$$

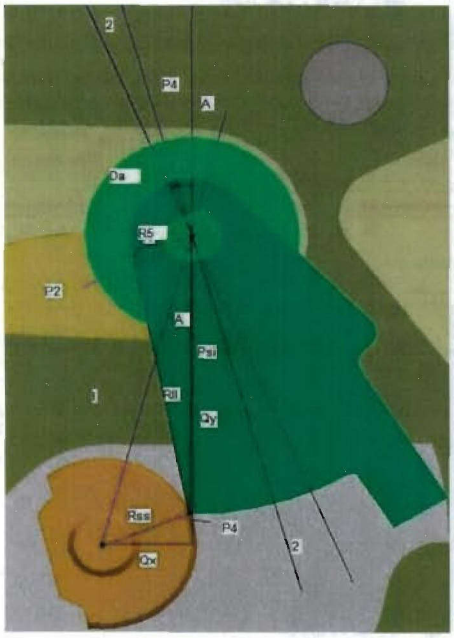
$$L = Qy + (Bh - Rdl)\cdot\sin(bang) + (BSh2 - Sls)\cdot\sin(pang)$$

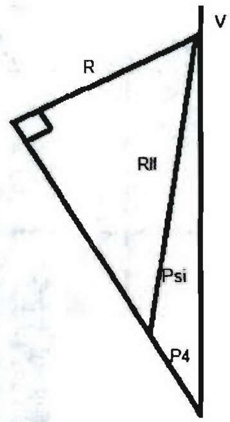
$$I = \sqrt{H2^2 + L^2}$$

$$\psi = \mathrm{atan}\left(\frac{H2}{L}\right) - \mathrm{acos}\left(\frac{Rl^2 - Rss^2 - I^2}{-2\cdot Rss\cdot I}\right)$$



(a)





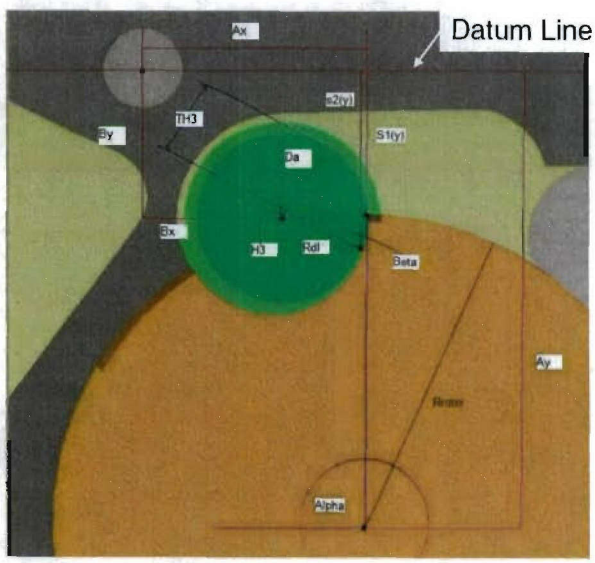
$$P4 = \pi - \operatorname{acos}\left(\frac{R5}{Rdl}\right) + \psi$$

$$Da = P4 + 2\left(\frac{\pi}{180}\right)$$

(b)

$$H3 = Rdl - TH3$$

$$\beta = \frac{-\pi}{2} + Da + \operatorname{acos}\left(\frac{H3}{Rdl}\right)$$



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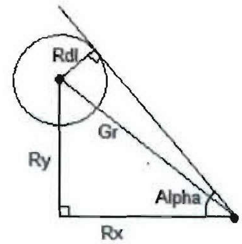
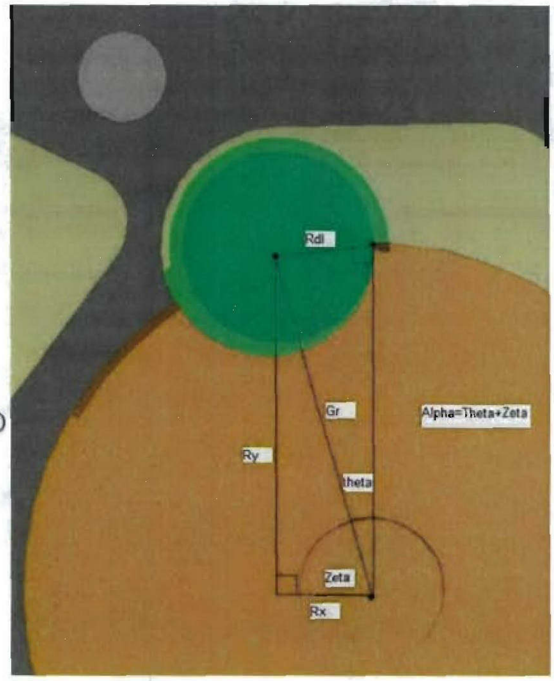


$$Ry = Ay + (Ah - axle)\cdot\sin(angle) - By + (Bh - Rdl)\cdot\sin(bang)$$

$$Rx = Ax + (Ah - axle)\cdot\cos(angle) - Bx + (Bh - Rdl)\cdot\cos(bang)$$

$$Gr = \sqrt{Ry^2 + Rx^2}$$

$$\alpha = \mathrm{atan}\left(\frac{Ry}{Rx}\right) + \mathrm{asin}\left(\frac{Rdl}{Gr}\right)$$



(d)

Figure 3
Dimensions and equations used for analysis

The dimensions left out of figure 3 are locating angles: bang, angle, and pang. Locating angles define where the axle touches the mating hole. These angles ranged between zero and 2π radians.

RESULTS

Probability of Failure

The results of the Monte Carlo simulation indicated that the mechanism would fail to lock in less than one in a million devices. The First Order Reliability method used 137 iterations and returned a First Order Reliability of approximately 0.9999678.

Sensitivity Analysis

The First Order Reliability simulation was also used for a sensitivity analysis. The dimensions and tolerances that have the largest effect on the reliability calculations were determined. Sensitivity analyses were completed on the average and tolerance range for each dimension.

Figure 4 shows the relative sensitivity of the average dimensions. Some values are in the positive y region and some values are in the negative y region. If the value is positive, then an increase in the average dimension will increase reliability. Increasing the average dimension for

by, **rrotor**, **radius5**, **qy**, and **th3** would increase the reliability of the FS&A; for example, a dimension such as 100 ± 0.05. The importance of each dimension to the reliability is shown by its magnitude. For example, if the nominal dimension of **rrotor** is raised by 20%, the reliability will increase more than if the nominal dimension of **qy** is raised by 20%. If the value in figure 4 is negative, a decrease in the average value of **ay** and **rll** will increase the reliability. When changing the nominal values, the tolerances remain the same.

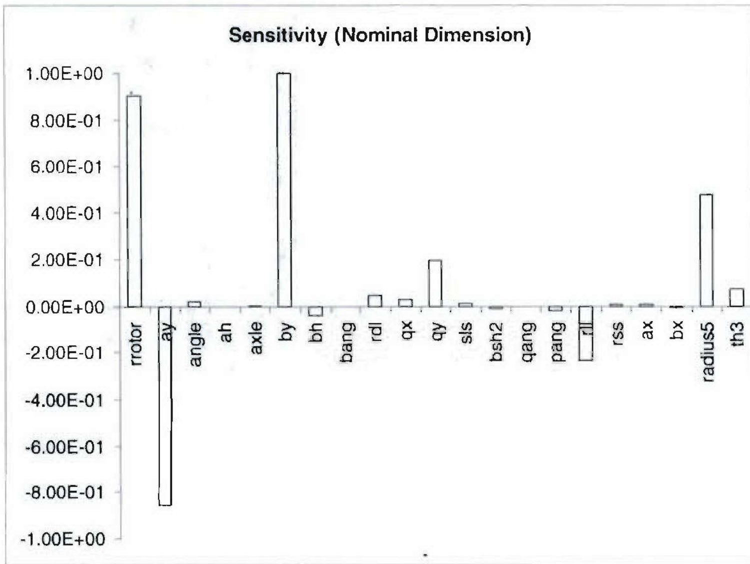


Figure 4
Sensitivity of reliability to average dimensions
(comparison of the Mean*dbeta/dmean for each constant)

The sensitivity analysis of the mean values was checked using Excel. Equation 1 was generated at mean values. Results were compared to results where constants were increased by 20%. In each case, the sensitivity in the Excel calculations agreed with the Unipass ranking.

Figure 5 compares standard deviations. If the value is below 0, then a tighter tolerance will improve reliability. If the value is above 0, then increasing the tolerance improves the reliability. From figure 5, decreasing the tolerances on dimensions **radius5** and **by** would improve the reliability of the FS&A. The tolerances of **pang**, **angle**, and **bang** cannot be decreased because they are locating angles with a value of $\pi \pm \pi$ radians. Not surprising, increasing the tolerances will not improve the reliability of the FS&A. However, figure 5 shows which tolerances have minimal effect on reliability. This information could be used to generate inspection criteria or decrease the cost of manufacturing.

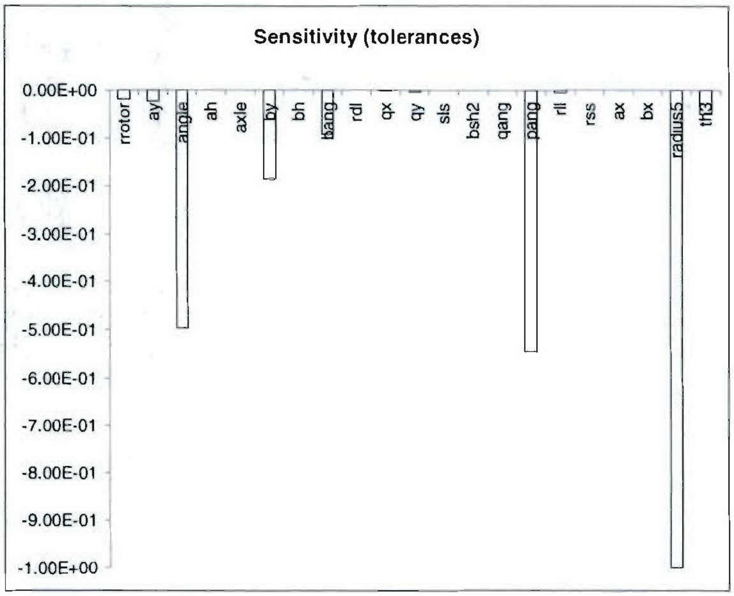


Figure 5
Sensitivity of reliability to standard deviations
(function: dbeta/d_standard deviation)

The sensitivity analysis also indicates dimensions that do not significantly affect the reliability of the FS&A. The following dimensions have minimal effect on the locking mechanism: ah, axle, sls, bsh2, qang, rss, ax, and bx.

DISCUSSION

Sources of Error

Errors in Accuracy

The methods provide an estimate of reliability and a ranking of the dimensions and tolerances that affect the reliable function of the FS&A. The actual distributions of the dimensions are unknown. Without the exact distributions, the reliability values should be considered as an order-of-magnitude answer rather than an absolute reliability value.

Errors in the Dimensional Variations

It was assumed that dimensions have a uniform distribution between the hard upper and hard lower boundaries (fig. 2). If the actual dimensions of multiple parts could be tracked, the accuracy of the distribution in figure 2 could be assessed and improved.

Errors Due to Inspection

It was assumed that all dimensions would be inspected 100% and that all inspections would be accurate. If the inspection is inaccurate or if only partial inspection is completed, then the hard boundaries shown in figure 2 are inaccurate. Soft boundaries could be used to incorporate probability density functions for XL and XU.

Errors in the First Order Method

Another source of error is in the First Order Reliability method. As shown in figure 6, this method assumes that there is a straight line that separates the regions of pass and failure. This may not be the case.

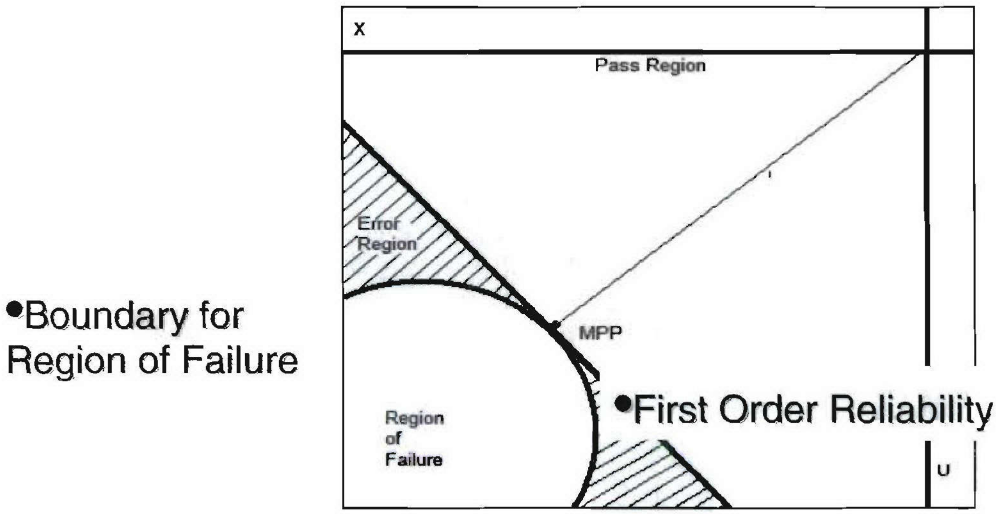


Figure 6
First order reliability method, error region

Using this Case Study for Inspection Criteria

The sensitivity analysis has implications for component inspection. From the sensitivity analysis, the following dimensions should be inspected to 100% or inspected as a safety critical characteristic:

- Based on sensitivity of the mean, 100% inspection: ay, rrotor, by, qy, rll, radius5
- Based on sensitivity of the standard deviation, 100% inspection: radius5, by

In a similar fashion, some of the variables had little effect on the reliability of the FS&A. Based on successful locking of the FS&A only, inspection to less than 100% might not be required for variables: ah, axle, sls, bsh2, qang, rss, ax, and bx. These eight variables may, however, contribute to other critical functions and for other reasons require 100% inspection.

CONCLUSIONS AND RECOMMENDATIONS

The predicated reliability of the fuze safe and arm (FS&A) mechanism is on the order of about 0.9999. This probability of success is consistent with the Excalibur's key performance parameter for reliability, 90%. To assure this FS&A performance, however, the following dimensions should be inspected 100%: radius5, by, axle, rroter, qy, th3, ay, and rll.

If improvements to the estimated reliability are desired, the following changes should be considered:

- Dimensions: axle, rrotor, radius5, qy, and th3; average dimension could increase; tolerances can remain the same
- Dimensions: ay, rll; average value could decrease; tolerances can remain the same
- Dimensions radius5, by; average dimension can remain the same; tolerances could decrease

The extent of the changes would depend on cost and manufacturability of the individual parts. If dimensional changes are made, the reliability estimate should be revised. The extent of changes should also depend on the reliability of the FS&A functioning properly. Changing the dimensions to increase the Reliability to Safety may decrease the reliability of the FS&A arming correctly.

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